JOURNAL OF MATERIALS SCIENCE **34** (1999) 5159–5162

An evaluation of the tribological performance of zirconia and CoCrMo femoral heads

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Five new zirconia, five new CoCrMo and three explanted CoCrMo femoral heads were wear-tested in bovine serum for five million cycles using the Durham Hip Joint Wear Simulator. Wear was measured gravimetrically and surface topography with a 3D non-contacting profilometer. This allowed an evaluation of the different head types on UHMWPE acetabular cup wear rates and the effect of roughening of the femoral head on acetabular cup wear. The mean acetabular cup wear rate against the five CoCrMo femoral heads was 40.8 $mm^3/10^6$ cycles which was significantly higher ($p = 0.03$) than against zirconia (33.3 $mm^3/10^6$ cycles). The initial surface roughness of the CoCrMo femoral heads ($R_a = 4.6$ nm) was statistically significantly higher than for the zirconia heads ($R_a = 3.1$ nm). Over the wear test the CoCrMo heads got statistically significantly rougher ($R_a = 10.5$ nm) whilst the zirconia heads showed no statistically signficant change. The three explanted CoCrMo femoral heads had initial mean surface roughness, R_a, values of 19, 24 and 55 nm with corresponding cup wear rates of 97.6, 131.2 and 148.4 $mm^3/10^6$ cycles respectively. The very high wear rates against the explanted heads highlight the need for scratch resistant femoral head surfaces.

1. Introduction

Loosening is the most common cause of failure in artificial hip joints [1] and this is generally thought to be caused by osteolysis induced by particulate debris [2]. Clinical evidence is growing to suggest that the total volume of wear debris of a particular size is important to loosening [3, 4] suggesting that the polyethylene wear rate will determine how long the joint replacement procedure will last.

The aim of this study was to compare the wear rates of UHMWPE against standard production zirconia and CoCrMo femoral heads and to evaluate how the wear rate changes when femoral components have been roughened by service in the body. A study of how the surface topography changes for each material over the duration of the wear test allows evaluation of the scratch resistance of each material whilst wear rates of UHMWPE against explanted CoCrMo femoral heads indicates how rougher femoral components might accelerate failure of an implant.

2. Materials and Methods

The Durham hip joint simulator [5] tests up to five anatomically mounted hip joints simultaneously. These are subjected to a dynamic motion and loading cycle. A sixth creep station applies a dynamic load across the prosthesis without any motion. The five articulating stations combine flexion/extension of the femoral component, with internal/external rotation of the acetabular cup. The combination of physiological motion and loading cycles resulted in a three dimensional locus of the load vector over the acetabular component, as seen *in vivo* and as used by Brummitt and Hardaker [6].

The simulator uses one DC servo motor and gearbox to drive the flexion/extension mechanism which was common to all articulating stations. A second DC servo motor and gearbox drives the pelvic rotation mechanism and this was also common to all articulating stations. Identical resultant joint forces across each prosthesis were acheived by having all six actuators supplied from a single manifold. Pressure to the manifold was supplied using a pneumatic proportional valve.

Ten new femoral heads were tested in the simulator. In the first wear test two articulating zirconia and three articulating CoCrMo femoral heads were used, and in the second wear test three zirconia and two CoCrMo femoral heads were used. Three explanted femoral heads were also tested in a third simulator run. The ten new femoral heads were 28 mm diameter Howmedica products (zirconia femoral heads Ref: 4653-40, CoCrMo femoral heads Ref 4653-01), and the 28 mm diameter acetabular cups used in all the wear testing came from one batch at manufacture (UHMWPE Ref 4840-2856 Lot T241633, Sterilised May 1995 Lot 55301). The three 28 mm diameter explanted CoCrMo femoral heads used in the wear tests were retrieved during revision surgery by Mr. Ian M. Pinder at the Freeman Hospital, Newcastle-Upon-Tyne. The explanted joints and patient details are summarized in Table I. All three heads exhibited some surgical damage from retrieval. However, in all cases the damage was

TABLE I Patient and joint type details

Case	Gender	Age at primary (/years)	Reason for primary	Mass (/kg)	Implant duration (/months)	Joint type
A	f	31	CDH	55	39	PCA, Howmedica
B	f	33	CDH	51	62	PCA, Howmedica
C	m	74	RA	59	16	Ultima, J & J

at the base of the head and sufficiently distant from the area of contact with the acetabular cup as to be unimportant.

The wear tests were conducted in a lubricant of 25% v/v newborn calf serum with 0.1% m/v sodium azide to retard bacterial growth. (The bovine serum used in all three wear tests was from the same supplier and batch. Harlan Sera-Lab Ltd., Batch 6030207.) Wear rates of the UHMWPE acetabular cups were measured gravimetrically [5].

The surface topography of all the femoral heads was measured before and after wear testing using a Zygo NewView 100 non-contacting optical interference profilometer. Images were taken using 400 times magnification giving a coverage of 180 by 135 μm. The horizontal resolution was consequently 0.56 μm/pixel and the vertical resolution was sub-nanometres. Prior to calculation of the surface parameters the spherical form of the femoral head was removed mathematically. When measuring the new femoral heads, both before and after wear testing, 26 points on each head were measured with the points arranged on the pole and then on annuli at 5°, 10°, 15°, 20° and 25° around the pole. The mean value of each surface parameter was calculated from all 26 points for each head. When measuring the surface topography of the explanted heads 10 points were selected from the worn region followed by 4 points from the peripheral region. The mean value of each surface parameter was calculated from the points in the worn region.

The results of the wear tests were then analysed statistically using the Stata 4.0 analysis package [7]. Normality was tested by applying Shapiro-Wilk and Shapiro-Francia tests. Equality of means was tested using *t* tests and Wilcoxon rank-sum tests were used to examine the equality of medians where applicable.

3. Results

The wear rates quoted for the acetabular cups against all the femoral heads are for the region of 2–5 million cycles as the wear rates of cups against new femoral heads has been shown to be statistically higher during the initial two million cycles as the prostheses wear-in [5].

3.1. Zirconia femoral heads

The mean UHMWPE acetabular cup wear rate against the five new zirconia femoral heads was 33.3 $mm^3/10^6$ cycles. Table II shows some of the measured surface parameters before and after wear testing for the zirconia femoral heads. The mean values of each surface parameter for the five heads are given and the surface parameters quoted are defined in Table III. No statistical difference was observed in any of the surface parameters for the zirconia femoral heads over the duration of the wear test.

TABLE II Femoral head surface parameter values before and after wear testing

Head	No. of cycles	R_a (nm)	R_{max} (nm)	R_{pk} (nm)	R_k (nm)	V1 (cu μm)	R_{sk}
Zirconia	zero	3.1	56	3.3	9.7	3.6	−0.4
	5×10^6	3.0	95	3.6	9.4	4.1	−0.8
CoCrMo	zero	4.6	180	5.2	13.2	6.1	−2.5
	5×10^6	10.5	571	18.1	22.1	26.9	−1.3
A	zero	19	802	11	25	15	−5.9
	5×10^6	17	1466	14	24	15	−5.8
B	zero	55	2020	133	96	200	−0.3
	5×10^6	49	2026	110	89	139	−0.9
C	zero	24	1046	22	38	25	−4.9
	5×10^6	20	1415	30	45	32	−4.8

3.2. CoCrMo femoral heads

For the acetabular cups articulating against the new CoCrMo femoral heads the mean wear rate was 40.8 $mm^3/10^6$ cys. The surface parameters for the new CoCrMo femoral heads are shown in Table II before and after wear testing. For most surface parameters the CoCrMo heads were statistically significantly rougher than the new zirconia femoral heads. For example, R_{max} was significantly different at $p = 0.009$ and surface roughness, R_a, at $p = 0.02$. The new CoCrMo femoral heads generally roughened over the wear test and this was confirmed as being statistically significant for most of the parameters measured. For example, R_{pk} was significantly different at $p = 0.0018$ over the wear test and R_{max} at $p = 0.0078$. For the parameters shown in Table II, all except skewness were significantly different over the wear test.

3.3. Explanted femoral heads

The acetabular cup wear rates against the three explanted femoral heads, cases A, B and C, were 97.6, 148.4 and 131.2 $mm^3/10^6$ cys respectively. Due to the high acetabular cup wear rates against the explanted heads no wear-in period was evident as it was so rapid. Statistical examination of the data confirmed this observation. However, for consistency the acetabular cup wear rates quoted are for the region of 2 to 5 million cycles similar to the data for the new femoral heads.

The surface parameters for each of the explanted femoral heads are also shown in Table II. It can be noted that the parameters vary before and after wear testing. However, there was no statistical difference in any of the parameters over the duration of the wear test indicating no surface damage or improvement of the heads caused by the tests. The variations in the surface parameters can be attributed to sampling errors due to spatial topographic differences. Confidence in the values shown and statistics performed is given by the number of points taken on each femoral head.

TABLE III Surface parameter definitions

Parameter	Definition	Description
Arithmetic mean roughness, R_a	$R_a = \frac{1}{l_x l_y} \int_0^{l_x} \int_0^{l_y} \lvert\eta\rvert \, dx \, dy$	Widely used and specified in BS 7251 Part 4 for the maximum line roughness of the metallic component.
Highest peak height, R_{max}	The height from the mean plane to the highest peak.	Characterizes possibly the most damaging individual feature.
Reduced peak height, R_{pk}	The top portion of the surface profile exceeding the core height.	Gives information on the damaging top portion of the surface.
Core roughness depth, R_k	The depth of the roughness profile excluding prominent peaks and grooves.	The working part of the surface influencing tribological performance.
Material filled profile peak volume, V_1	The volume of the peaks exceeding the core height.	Volume of material most likely to influence polymer wear.
Skewness, R_{sk}	$R_{sk} = \frac{1}{S_q^3} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \eta^3(x, y) p(\eta) \, dx \, dy$	Statistical term describing the shape of the amplitude distribution. Low negative values are indicative of good bearing surfaces.

4. Discussion

4.1. Acetabular wear against zirconia femoral heads

The mean wear rate of the UHMWPE acetabular cups when tested against zirconia ceramic heads was found to be 33.3 $mm^3/10^6$ cys. In comparable simulator studies in which Barbour *et al.* used the Leeds PA II simulator with zirconia femoral heads, UHMWPE acetabular cups and bovine serum lubricant all from the same batches as used in this study, they obtained an acetabular wear rate of 30.0 $mm^3/10^6$ cys [8]. Thus direct corroboration of these results was obtained from these two independent studies.

In another study of 28 mm diameter alumina ceramic femoral heads, Clarke *et al.* [9, 10] found UHMWPE acetabular wear rates of 35.0 and 32.8 $mm^3/10^6$ cys. This again supports the values obtained in the present study.

4.2. Acetabular wear against CoCrMo femoral heads

CoCrMo alloy femoral head components gave a cup wear rate of 48.1 $mm^3/10^6$ cys in this study. This was comparable with a number of other workers results. In a radiographic study Livermore *et al.* found 28 mm diameter prostheses wore at a rate of 48.4 $mm^3/10^6$ yr [11]. Since it is normally assumed that an average one year of use corresponds to one million cycles [12] these results are very close. McKellop *et al.* [13] using titanium and 316 stainless steel heads found wear rates of 39 and 55 $mm^3/10^6$ cys respectively when lubricated in bovine serum.

4.3. Production surface finish comparison between zirconia and CoCrMo femoral components

Zirconia femoral heads generated 33.3 $mm^3/10^6$ cys of UHMWPE wear debris whilst CoCrMo heads produced 48.1 $mm^3/10^6$ cys under identical conditions. This was statistically significant ($p = 0.03$). For all surface parameters, except skewness, the zirconia femoral heads were smoother than the CoCrMo femoral heads prior to wear testing. Skewness is a statistical term describing the shape of the amplitude distribution and low negative values are indicative of a good bearing surface. It is therefore unsurprising that there is no statistical difference in skewness between the femoral heads as they are excellent bearing surfaces. Therefore, since the standard production surface finish of the zirconia femoral heads is superior to the CoCrMo heads, this gives a significant reduction in UHMWPE acetabular cup wear rate.

4.4. Changes in femoral head surface roughness with use

Over the duration of the wear test there were no statistically significant changes in any of the surface parameters for the zirconia heads. When examining the CoCrMo femoral heads, the surfaces generally roughened to an extent that was statistically significant for most surface parameters. Zirconia femoral heads therefore showed improved scratch resistance over CoCrMo femoral heads which is likely to lead to longer life than joints with CoCrMo femoral head components.

4.5. Wear rates of new acetabular cups against explanted heads

It is generally considered that simulator wear tests produce lower wear rates than those for similar prostheses worn *in vivo* [14]. The reasons given for this are several including the fact that it is highly unlikely that bone or cement particles could contaminate the joint space in a simulator whereas *in vivo* this can occur causing possible damage to both the femoral head and acetabular cup. (Two of the explanted heads tested here were cementless which eliminated the possibility of cement contaminating the joint space.) UHMWPE acetabular cups tested *in vitro* have frequently had shorter post irradiation ageing than cups which have been implanted which has been shown to lead to lower wear rates [15]. The motion and loading cycles applied by simulators are generally smooth, continuous walking patterns without the extremes which can be seen clinically when a patient may run, climb or descend stairs, rise from a chair, or even trip and possibly fall.

Although the simulator wear rate results are generally lower than clinical wear rates, in the case of the explanted joints tested against new UHMWPE cups the wear rates were alarmingly high. This is particularly so when considering that all three explanted heads fall within the current British Standard surface roughness value of 50 nm for new femoral heads. The wear rates are far higher than the radiographic study already referred to, and even exceed 28 mm diameter explant studies such as that of Kabo *et al.* [16] who found a wear rate of 75.6 $mm^3/10^6$ yr.

It has been proposed that loosening of an implant is related to the total volume of wear debris [3, 4]. This study has shown, using explanted femoral components, that once the femoral head becomes roughened the acetabular cup wear rate rises substantially. The osteolytic response to wear debris will consequently be induced far quicker and the implant will fail prematurely.

5. Conclusion

The results of this *in vitro* study indicate that the use of zirconia femoral may extend the useful implantation periods of total hip arthroplasty compared with CoCrMo heads. For the new standard production femoral heads tested in this study, zirconia femoral heads have a superior surface finish compared with CoCrMo femoral heads. The zirconia femoral heads were also more scratch resistant than the CoCrMo heads. Therefore, use of zirconia heads would prevent the extremely high wear rates observed in this test with explanted CoCrMo femoral heads.

Acknowledgements

The authors would like to the thank the Department of Trade and Industry for funding this project. The new femoral heads and acetabular cups used in the wear testing were generously provided by Howmedica Inc. The explanted femoral heads and patient details were provided by Mr. I. M. Pinder at the Freeman hospital, Newcastle-upon-Tyne.

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Received 23 February
and accepted 20 April 1999